Impact of seismic surveys on marine life

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The possible impact of marine seismic surveys on marine life has been of great concern for many years. The discussion is, however, characterized by confusion over sound-level terms and measurements, as well as an apparent misunderstanding of the nature of seismic signals. This paper will review underwater sound and the nature of impulse sound as it may impact marine life in general.

Sound levels. A seismic signal is quantified by a variety of measures in the time and frequency domains. Factors such as peak pressure and the rate of pressure change have impact on the quality of the seismic data. But they will also be of importance for the evaluation of possible impact that the signals may have on marine life. Pressure output from the source is measured in Newton/m^2 or Pascal (Pa) but is most often given on a decibel scale.

Intensity and effective sound pressure (P_e) are related through the equation

$$I=\frac{P_e^2}{\rho_0 c}$$

where ρ_0 is the specific density and c is the propagation speed of sound.

This gives the basis for the decibel scale for sound intensity or pressure as

$$dB=10\log\frac{I_1}{I_0}=20\log\frac{P}{P_0}$$

where I_0 is the reference intensity level (watts/m^2) and P_0 is the reference pressure in Newton/m2 (Pascal) $\rho_0 c$ is often referred to as the acoustic impedance of the medium. A value of 415 is used for air and 1.54 × 106 is the standard value for seawater.

Sound intensity, or pressure, will cause an amplitude displacement of molecules that is given by

$$A=\frac{1}{\omega}\sqrt{\frac{I}{\rho_0 c}}=\frac{P}{\omega\rho_0 c}$$

The lower limit of hearing for the human ear corresponds to a pressure level of 20.4 μPa. This value is used as the reference pressure for acoustic measurements in air. In water the reference pressure is 1 μPa. The difference between these reference pressures is 26 dB.

In water, due to the higher acoustic impedance, similar sound intensities will give a pressure that in water is 61 times lower than that in air, or a difference of 35.6 dB.

Correcting for the difference in reference level and the specific acoustic impedance, 62 dB must be added to measurements in air to compare with measurements taken in water.

Table 1 gives some corresponding values for air and water having the same intensities at a frequency of 1 kHz.

Assuming that the lower limit of human hearing is connected to the intensity (and thereby the pressure or the amplitude displacement as given by the equations above) of the sound wave, Table 1 shows that in water the lower limit should be approximately 62 dB. This compares well with studies on human underwater hearing, showing that the hearing threshold is 67 dB re 1μPa for an 800-Hz signal (Parvin and Nedwell, 1995).

Table 1. Values for air and water

Pressure in air re. 20μPa	Pressure in water re. 1μPa	Comments
0	62	hearing threshold
60	122	office environment
120	182	feeling threshold
140	202	threshold of pain
160	222	threshold of direct damage

Sound measurements. Sound levels are measured in many ways:

The root mean square (rms) or the equivalent to a static pressure having the same power.
Zero to peak (0-p), or the maximum value measured from the zero line
Peak to peak (p-p), or the maximum negative-to-positive measurement of the signal. (This is the standard for specifying air-gun signal levels.)
Frequency spectrum gives the pressure as a function of frequency.

Other methods involve computation of an equivalent signal, using a variety of mathematical schemes. However, computation of the equivalent signal is difficult, and this technique must be used with great care.

The abundant research on the impact of noise on marine life gives data in a variety of ways, with different measurements and reference pressure. In most cases, however, units and measurements are not specified, making it difficult to compare results. Furthermore, when reference is made to papers in which proper specifications are given, there is a strong tendency to misinterpret the values and thereby make false comparisons.

To compare 0-p levels with rms levels, one must add 3 dB (assuming a sinusoidal signal, higher if noise is considered); for comparison with p-p levels, 9 dB must be added. Other methods may require even higher dB corrections to make direct comparisons. Spectral measurements, as are common for most noise analyses, involve a differentiation for each single frequency contributing to the broadband signal. This means that, for a seismic signal, approximately 40 dB must be added to the spectral levels for comparisons with broadband p-p measurements.

To place seismic signal levels in perspective, the pressure of low-level background noise (spectral level) is above 60 dB re 1 μPa (10-100 Hz). This corresponds to gentle wave action and little wind. In bad weather, low-frequency background noise increases to 90-100 dB re 1 μPa. Heavy ship traffic generates higher levels of background noise.

Marine vessels generate significant noise. Large tankers may have a source level of 170 dB re 1μPa (spectral level) at 1 meter; similarly the source level of active trawler will be in the order of 150-160 dB re 1μPa. Whales can generate signal levels exceeding 180 dB re 1μPa at 1 meter.

Signals from air guns are given as peak-to-peak (p-p) measurements, and they range from 210 to above 250 dB p-p re 1 μPa at 1 m (comparable to a spectral level of 170-210 dB per Hz re 1 μPa at 1 m). Chemical explosives detonating in the water column will have peak pressure levels in excess of 270 dB re 1 μPa at 1m, for charge sizes of 1 kg. However, chemical explosives are not used in seismic operations today.

The computed source level depends on the frequency range over which the acoustic pulse is measured. Seismic arrays are frequently measured over 0-125 Hz or 0-250 Hz. There may be a slight underestimation of total energy by these bandwidths, but the error is small because output above 250 Hz is limited. It is clear, however, that the output from air guns extends well into the kHz band but with much-reduced pressure level.

Sound propagation in water. Propagation of sound in the ocean is highly frequency dependent. Most procedures for modeling the propagation is developed for high-frequency sound. Low-frequency sound will penetrate into the seafloor, and therefore follow the propagation of a spherical wave. This is important when evaluating impact from marine seismic surveys. Another important factor is the depth at which the source is placed. Most studies of sound propagation use a source depth of 18 or 91 m. However, the seismic source is at 4-5 m. This implies that the impact of the surface reflection is much more important, resulting in significantly more attenuated sound than would result from a deeper source.

Sophisticated models for sound propagation may not be necessary in the evaluation of possible impact of seismic surveys. Because of the spherical spreading nature of the signals (with the source close to the water surface) and the attenuation of the signals in the geologic strata below the sea bottom, a simpler model can be used.

A practical formula for evaluating sound pressure at distance r from the seismic source is

$$P(r) = P(s) - A\log_{10}(r) - Br - C$$

where P(r) is the sound pressure at distance r, P(s) is the source level, A is the propagation type attenuation factor (A = 20 for spherical waves); B is a range dependent attenuation (on the order of 2-5 dB per km); and C is a fixed attenuation due to obstacles (in open sea this is 0)

For high-frequency signals, higher than about 1 kHz, more elaborate propagation models should be used.

The water depth and seafloor influence the propagation of seismic signals. But as the frequency of the signal is low, and the source is close to the sea surface, sound pressure at significant distance from the source is dominated by signals that have traveled through the subsurface. Standard underwater sound pressure modeling may therefore not be the right method for assessing the impact of seismic sources at larger distances.

The well-known ghost reflections (signals from the mirror image of the source) play an important role in assessment of sound propagation in the ocean. Due to the phase characteristic of the source and its mirror image, they will cancel each other at the sea surface, resulting in rapid decay of the waterborne seismic signal.

Sound channels frequently occur in the ocean, and sound generated in these will propagate for considerable distances. Although many consider these significant for seismic signals, the low-frequency nature of seismic signals and the shallow depth of the source mean little energy will be generated that can be propagated through sound channels.

A general observation is that seismic signals tend to be attenuated with a factor that is somewhat stronger than given by spherical spreading, regardless of water depth, temperature, and bottom conditions. It is therefore easy to overestimate sound-pressure levels at significant distances from seismic sources, giving an incorrect impression of possible impact they will have on marine life.

Environmental impact of marine seismic surveys. Since the early 1970s several studies have described the sensitivity of fish and marine mammals to high-level sound. The most comprehensive work on the subject is the 1995 book *Marine Mammals and Noise*. It includes an exhaustive list of references, and the book is recommended to anyone with interest in these topics.

Fish and marine mammals use sound for communication, navigation, and sensing. More than 50 fish families have sound-producing species and all marine mammals are vocal underwater.

Frequencies used by marine species vary over a large spectrum. Whales generate strong signals with frequencies as low as 20 Hz. Other marine animals generate sounds for echolocation that reach frequencies above 100 kHz. Fish normally generate sounds of 50-3000 Hz.

The frequency range of seismic signals coincides with the audiogram of many marine species and may therefore interfere with their normal behavior.

High-level sound may impact marine mammals in different ways. If the sound is really high and of significant duration, it may cause physical damage such as permanent hearing loss. Lower sound levels may cause temporary threshold shifts in hearing and may certainly influence the ability to communicate and navigate.

Impulsive sound also will impact fish and marine mammals, but the effects of this type of sound are not as well understood because most studies have investigated continuous or intermittent noise of considerable duration. Experiments in Norway using air guns and explosives concluded that after one exposure, little or no damage could be observed even after very high sound levels. Several exposures were needed to cause observable damage. Unfortunately, the studies concentrated on damage, and the "no-damage" findings from single exposures are not often included in the final report.

Several studies of direct physical damage by air guns on fish eggs and larvae confirm that signal levels exceeding 230-240 dB p-p re 1μPa are necessary for harm to occur. Therefore massive physical damage can only occur within a few meters from the air guns.

Changes to the behavior patterns of fish and marine mammals are potentially the largest impact caused by marine seismic surveys.

Many experiments have studied the effect of seismic activities on the behavior of fish and marine mammals. A report from the Scottish Fisheries Research Services shows that fish will continue to swim toward active air guns. The normal response to the sound impulse is a short side skip, followed by a return to normal swimming in the direction of the gun. Sound-pressure levels at the fish were on the order of 220 dB p-p re 1 μPa.

Studies on marine mammals use direct observations, often from airplanes, or analysis of their vocalizations and position as determined by hydrophones.

Many reports on behavioral change caused by seismic surveys are difficult to compare, because measurement methods and units are not documented properly. Unfortunately, there is no clear rule for defining sound levels that will inflict behavioral change, which leaves interpretation of the reports highly subjective.

Characteristics of impulse noise. The impact of impulsive

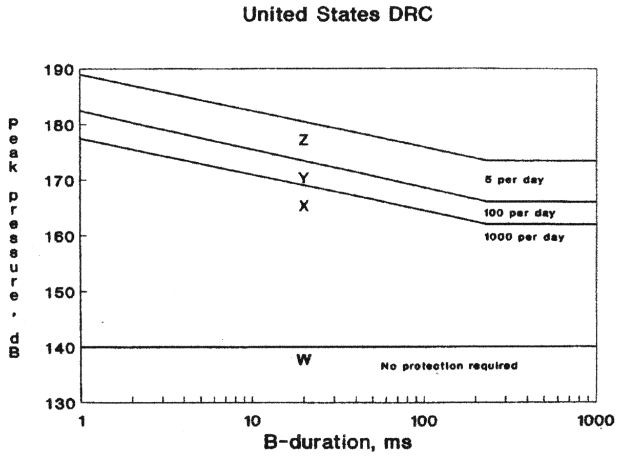

Figure 1. The CHABA recommendation for impulsive noise on humans.

sound on humans has been studied extensively, especially in regard to impulse noise from weapons. Based on these studies, most countries have given recommendations on daily exposure maxima.

In some areas it is required that the signals from seismic surveys reaching marine mammals must not exceed 180 dB rms re 1 μPa. There is no specification as to the duration of this exposure, or the number of impulses allowed if the noise is intermittent. It is therefore reasonable to assume that sound levels below 180 dB rms re 1 μPa represent a level that is not dangerously high for the animals, regardless of the duration of the exposure.

A sound-pressure level of 180 dB rms re 1 μPa corresponds to 190 dB p-p re 1 μPa if one uses the conversion factors for sinusoidal signal. If noise signals are considered the level will be even higher.

By comparison, CHABA specifications for impulse noise on humans (Figure 1) state "no protection required" below a level of 140 dB (0-p re 20 μPa). Converted to the water environment, this represents 202 dB 0-p re 1 μPa, or 208 dB p-p re 1 μPa. The CHABA specification compares well with the level of 180 dB rms re 1 μPa, provided one assumes that marine mammals have a lower threshold of hearing (about 20 dB below that of humans) and that the audiophysiological dynamic range is about the same.

If one assumes that seismic source strength of 250 dB p-p re 1 μPa, the analysis above would give a safe distance from the air-gun array of 1 km (60 dB loss due to spherical spreading).

The CHABA specifications indicate that if the number of impulses is fewer than 1000 per day, the acceptable sound level is increased by 20 dB; this reduces the distance to 100 m. A seismic vessel normally fires a source every 25 m, or 40 times over 1 km. This must mean that, unless the animals deliberately follow the vessel, a maximum of 40 impulses is emitted before the distance between the animal and the vessel is greater than the safe distance.

The use of the CHABA figures can be taken further, as the impulse sound level can be increased even more if there are only a few impulses.

An output of 250 dB p-p re 1μPa at 1 m from an air gun array is a theoretical value used for computational purposes only. It is computed from measurements vertically below the array. Due to the physical dimensions of the array, sound generation is spread over an area, and nowhere within the array will the pressure level exceed 235 dB p-p re 1μPa.

This should make it quite clear that a seismic vessel operating at 10 km/h cannot represent a physical danger to marine mammals, regardless of distance.

Conclusions. Air-gun operations cause little direct physical damage to fish at distances greater than 1-2 m from the source. It is evident that fish respond to sounds emitted from air guns. Reactions to the sound impulses are reported at levels from 180 dB re 1 μPa, but the full extent of the reactions is unknown.

Due to the avoidance behavior by free-swimming fish, they should not suffer physical damage from the airguns.

The catch rate near surveys can be affected, but the reduction in catch rates is not expected to be long lasting. The reason for reduced catches is probably because fish dive to the bottom or disperse when exposed to high-level sound.

It is standard industry practice to "ramp up" air guns when starting a survey to "warn" fish and marine mammals in the area.

Marine mammals clearly react to seismic signals at ranges of a few km, but the reactions may be due to curiosity rather than a direct negative effect on the animals.

Current research on possible impact of seismic surveys on marine life appears to neglect the literature on impulse sound on humans. Using this material may change some current restrictions on seismic operations in sensitive marine areas.

Suggestions for further reading. *Marine Mammals and Noise* by Richardson et al. (Academic Press Inc., 1995). CHABA (National Academy of Sciences, National Research Council, Committee on Hearing, Bioacoustics and Biomechanics), Proposed damage-risk criterion for impulse noise (gunfire) edited by Ward (Report of Working Group 47, 1968). "Scaring effects in fish and harmful effects on egg, larvae, and fry by offshore seismic explorations" by Dalen and Knutsen (in *Progress in Underwater Acoustics*, Symposium on Underwater Acoustics at Halifax, Nova Scotia, Plenum Publishing, 1986). "Effects of Seismic Shooting on Catch Availability of Cod and Haddock" by Engas et al. (Institute of Marine Research, Norway, 1993). *Review of the Effects of Underwater Sound Generated by Seismic Surveys on Cetaceans* by Evans and Nice (Report to UKOOA, 1996). *Seismic Exploration; Its Nature and Effect on Fish* by Falk and Engel (Technical Report Series No. CEN T-73-9. Resource Management Branch, Central Region (Environment), Canada, 1993). "Effects of sound from a geophysical survey device on behaviour of captive rockfish (sebastes spp.)" by Pearson et al. (*Canadian Journal of Fish and Aquatic Science*, 1992). *The Effects on Marine Fish, Diving Mammals and Birds of Underwater Sound Generated by Seismic Surveys* by Turnpenny and Nedwell (UKOOA, 1994). *Principles of Underwater Sound* Third Edition by Urick (Peninsula Publishing, Los Altos, California, 1983). "Seismic airgun effects on immature coho salmon" by Weinhold and Weaver (presented at SEG's 42nd Annual Meeting, 1972).

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